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Effect of High Temperature Exposure on the Mechanical Properties of Cold Expanded Open Holes in 7050-T7451 Aluminium Alloy

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ABSTRACT

Cold expansion of fastener holes has been widely used in the manufacture, maintenance and repair of airframe components to provide beneficial compressive residual stresses around fastener holes and to extend their fatigue life. However, some components may experience exposure to high temperatures due to operational, maintenance or accidental factors. The high temperature exposure could lead to relaxation of compressive residual stresses and potentially affect the component's properties such as fatigue life and static strength properties. This report summaries the investigation on the effect of exposure time at a temperature on the mechanical properties of cold expanded open holes in 7050-T7451 aluminium alloy. The experimental results show that for a given exposure temperature of 350°F (177°C), the fatigue life of the specimens decreased with increasing exposure time. When the exposure time exceeds 3 hours, the fatigue life remained relatively unchanged. The yield strength at the same exposure temperature fell below the minimum allowable value after 1 hour exposure.

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Effect of High Temperature Exposure on the Mechanical Properties of Cold Expanded Open Holes in 7050-T7451 Aluminium Alloy

Executive Summary

Cold expansion of fastener holes - also known as cold worked holes - is a mechanical treatment technology widely used in the manufacture of airframe components to provide beneficial compressive residual stresses around the fastener hole that delay or retard initiation and growth of fatigue cracks in that region, leading to extension or enhancement of their fatigue life. Cold expansion is generally used in components, which are exposed only to service conditions at ambient temperature. When cold expanded holes are exposed to elevated temperatures during service, e.g. due to maintenance or accidental factors such as fire, the relaxation of residual stresses could potentially affect their fatigue life. Thermal exposure could also affect the static strength properties of the material. To quantify this effect, this investigation examined the effect of thermal exposure on cold expanded open hole specimens manufactured using aluminium alloy AA7050-T7451 - a high strength aluminium alloy used in airframe components in civil and military aircraft.

As a result of exposure to a temperature of 350°F (177°C) for periods of time ranging from 1 to 8 hours:

(i) the fatigue life of the specimens decreased;
(ii) the yield strength decreased linearly with increased exposure time and fell below the minimum allowable value after 1 hour exposure;
(iii) the hardness (Rockwell scale, HRB) decreased as the exposure time increased; and,
(iv) the electrical conductivity (%IACS) increased with increasing exposure time, but remained within the specification limits set by AMS 2658B (SAE, 2003b).

The decrease in the fatigue life of cold expanded open-hole specimens with increasing exposure time was thought to be primarily due to the relaxation of the beneficial compressive residual stresses around the cold expanded hole. The experimental results indicated that whilst the fatigue life did decrease after exposure to 350°F (177°C), for a period of up to 8 hours, the fatigue life remained at levels of about 3 to 4 times that of non-cold expanded hole specimens. This result suggests that the compressive residual stresses introduced by the cold expansion process are relatively stable at the tested temperature.

Contents

1. Introduction

Aluminium alloy aircraft components may experience overheating due to thermal exposure during service, because of operational factors, or during maintenance procedures such as the application of composite bonded repairs that may involve high temperature curing cycles. Other factors contributing to high temperature exposure, resulting in thermal damage to the tailored microstructure of metallic components of aircraft, include (Hagemaier, 1982; Gammon, et al., 2000; Lacarac, et al. 2001):

- accidental fire,
- leakage of hot gases from broken or cracked hot-air ducts in the engine bay area,
- long-term service exposure from the auxiliary power unit (APU) or engine exhaust,
- aerodynamic heating during supersonic flight speeds,
- high temperatures generated near engine components,
- aircraft sitting idle on a runway in the sun, and
- lightning damage.

The effect of thermal damage on metallic materials is a degradation of static strength (yield and tensile strengths) at the exposed temperature, a degradation of static strength at room temperature after exposure to a higher temperature, the relaxation of beneficial compressive residual stresses and, potentially, some degradation of environmental cracking resistance of the affected material. The degree to which the thermal exposure will affect component material properties is dependent upon several factors including temperature and duration of exposure, thermal conductivity, alloy temper, surface treatment (e.g. peening and corrosion protection schemes used), and the thickness and configuration of the component. Generally, the higher the exposure temperature and the longer the exposure time, the greater the likelihood of degradation in the mechanical properties of the material.

Roth and Wortman (2002) investigated the effects of low and high temperature cure cycles, used by the Canadian Forces for adhesive bonding of a composite doubler to a shot peened aluminium alloy (7050-T7451) component, on the relaxation of residual stresses and fatigue crack initiation behaviour under a fighter aircraft spectrum loading. The results showed that the heat cycle (at least 1 hour at 250^{o}F (121^{o}C)) used for adhesive bonding, induced relaxation of the peening residual stresses and reduced the time to form a crack.

Douchant, et al. (1999) evaluated the fatigue properties of fighter aircraft aft fuselage formers (made of AA7050-T7451 aluminium alloy) exposed to heat passing through the firewall from a damaged engine. For one hour exposure at 600^{o}F (316^{o}C), the static tensile and cyclic strengths were reduced by 50% of the pristine material. The strain-life also decreased for that temperature and time of exposure.

Currently, heat damaged structures are assumed (based on hardness and electrical conductivity criteria) to be in an annealed (soft) condition, and the heat damaged airframe

structural components are replaced at a considerable cost burden to the through-life support programs of the fleet.

Many structural airframe assemblies are joined by inserting fasteners through holes. The fastener holes have a high stress concentration at the edge of the hole and are sources of fatigue crack initiation resulting in fatigue failures in airframe structures (Buxbaum & Huth, 1987). A relatively simple and cost-effective technology to improve the fatigue resistance of fastener holes is the split-sleeve cold expansion of fastener holes (Reid, 1993). Cold expansion of fastener holes - also known as cold worked holes - is a mechanical treatment technology widely used during airframe manufacture to provide beneficial compressive residual stresses around fastener holes that delay fatigue crack initiation and growth, leading to an extension in the fatigue life of components (Patrak & Stewart, 1974; Mann, et al. 1984; Ball & Lowry, 1998). Cold expansion is generally employed in components which are exposed to service conditions at ambient temperature.

Clark and Johnson (2003) studied residual stress relaxation around fastener holes due to thermal exposure at 219°F (104°C) for 250 hours in aluminium alloy AA7050-T7451. The relaxation was quantified by a drop in residual stress of 13.6%. They concluded that the residual stress relaxation could be more significant at temperatures higher than 219°F (104°C) and that, depending on the applied cyclic stress, the fatigue properties could also be affected by thermal exposure at the indicated temperature. Lacarac et al. (2001) reported the results from residual stress and fatigue crack growth measurements in the high temperature resistant, advanced supersonic transport aluminium alloy AA2650 containing cold expanded (4%) holes that were exposed to room (68°F (20°C)) and high (302°F (150°C)) temperatures under loading conditions. The authors concluded that exposure to high temperature alone relaxed the residual stresses introduced by cold expansion. They also noted that specimens containing cold expanded holes that were exposed to a temperature of 302°F (150°C) had higher fatigue crack growth rates compared to the fatigue crack growth rates in specimens that contained cold expanded holes but were not exposed to high temperature.

In addition, the residual stress state may not be stable during cyclic loading. The global and local residual stress distributions will change if the residual strength is exceeded by the sum of the applied stress and the residual stress, particularly for the local residual stress distribution. As a result, relaxation of residual stresses could lead to reduced effectiveness of the fatigue life enhancement achievable from mechanical treatments such as cold expansion and shot peening. At elevated temperatures, the relaxation of residual stresses would significantly affect fatigue life. However, the exposure temperature and loading conditions would determine whether the beneficial effect from the cold expansion process is still retained to provide the intended fatigue life improvement. There is very limited published data on the effect of temperature on the retention of fatigue life improvements associated with cold expansion of fastener holes (Lacarac, et al., 2001).

This Technical Note presents the results to date of a DSTO investigation into whether the fatigue life improvement for aluminium alloy AA7050-T7451 coupons containing cold expanded open holes is retained after thermal exposure. The cold expansion was applied using the Fatigue Technologies Incorporated (FTI) standard split-sleeve cold expansion

procedure (FTI, 2002) prior to thermal exposure at the selected temperature of 350°F (177°C) for exposure times of 1, 3, 6 and 8 hours. The exposure temperature and times were chosen to simulate possible thermal exposure effects arising from candidate, in-situ composite bonded repair processes and potential in-service operating temperature conditions in aircraft structures or components. In this work program, the focus was on assessing the fatigue life of AA7050 aluminium alloy specimens after cold expansion and thermal exposure. Static yield and ultimate tensile strength measurements on cylindrical specimens, as well as electrical conductivity and hardness measurements of cold expanded open hole specimens for thermal exposure times of 0, 1, 3, 6 and 8 hours were also included in the experiments.

2. Experimental Details

2.1 Material and Specimen Geometry

2.1.1 Material

The material used in this investigation was AA7050-T7451 aluminium-zinc-magnesium-copper alloy derived from two different supply sources with two plate thicknesses of 5-inch (127 mm), (designated 'KK') and 0.375-inch (9.5 mm), (designated 'LM'). The material conformed to Aerospace Materials Specification, AMS 4050E with respect to chemical composition and mechanical properties (SAE, 2003a). AA7050 aluminium alloy is commonly used in the manufacture of bulkheads and other airframe components for military aircraft. The chemical compositions (wt %) of the plates shown on the suppliers' test certificates are reproduced in Table 1. The longitudinal (L) direction mechanical properties, as provided by the material suppliers are also shown in Table 2. The reported electrical conductivity in each case was 41.2 (%IACS).

Table 1. Chemical Compositions (wt %) of 7050-T7451 Aluminium Alloy

Designation	Al	Cu	Mn	Si	Mg	Zn	Fe	Ti	Zr
KK	bal	2.12	0.01	0.03	2.25	6.06	0.08	0.035	0.11
LM	bal	2.21	0.01	0.03	2.11	6.07	0.08	0.03	0.08

Table 2. Longitudinal (L) mechanical Properties of 7050-T7451 Aluminium Alloy

Designation	Yield Strength, MPa (ksi)	Ultimate Strength, MPa (ksi)	Elongation (%)
KK	447 (64.8)	513 (74.4)	8
LM	450 (65.3)	513 (74.5)	15.6

2.1.2 Specimen Geometry

The specimens used in this study were manufactured with the specimen loading axis aligned parallel to the rolling direction (longitudinal - L) of the plate. Two types of specimen geometry were selected. Geometry-1, shown in Figure 1, contained a 0.25 inch (6.35 mm) diameter open hole at the centre. The thickness and gauge width of the Geometry-1 specimens were 0.39 inch (10 mm) and 1.26 inch (32 mm), respectively. The specimens were machined from 5-inch (127 mm) thick AA7050-T7451 aluminium alloy plate (i.e., KK plate material).

Geometry-2 specimens were machined from 0.375-inch (9.5 mm) thick AA7050-T7451 aluminium alloy plate (LM plate material) to a thickness of 0.25 inch (6.35 mm) and the specimen geometry, with a continuous radius in the gauge section, is shown in Figure 2. In

addition, Geometry-2 specimens without the open hole were used as baseline specimens. For the tensile tests, cylindrical specimens were used and the corresponding geometry is illustrated in Figure 3.

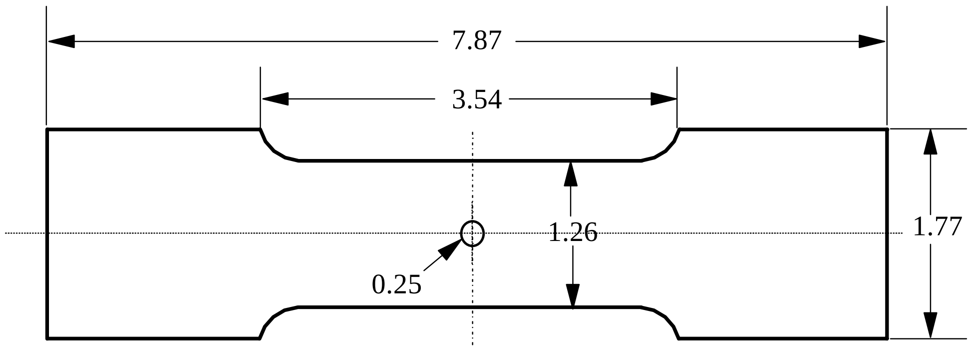


Figure 1. Specimen geometry (Geometry-1) and dimensions with the straight gauge section. The units are in inches (not to scale). The thickness is 0.39″ (10 mm) and the gauge width is 1.26″ (32 mm). The hole diameter is 0.25″ (6.35 mm). Notes: 7.87″ = 200 mm, 3.54″ = 90 m and 1.77″ = 45 mm.

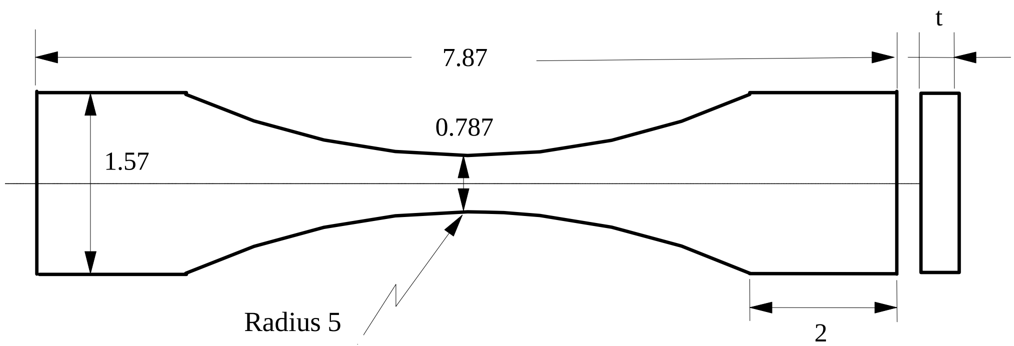


Figure 2. Specimen geometry (Geometry-2) and dimensions with a continuous radius gauge section. The units are in inches (not to scale). The thickness is 0.25″ (6.35 mm), the length is 7.87″ (200 mm), the gauge width is 0.787″ (20 mm), and the radius is 5″ (127 mm).

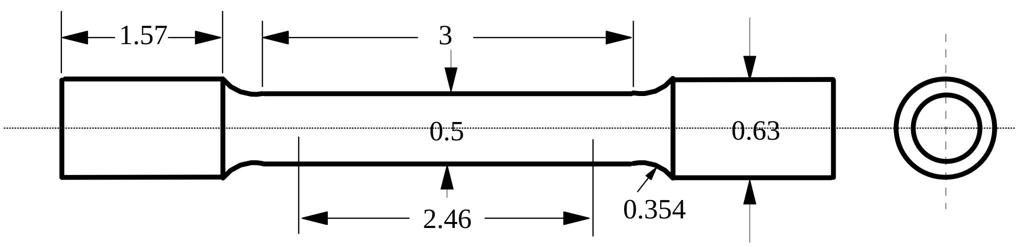


Figure 3. Cylindrical specimen geometry used for tensile testing. The units are in inches (not to scale). The diameter at the gauge length is 0.5″ (12.5 mm), the gauge length is 2.46″ (62.5 mm), the length of the reduced section is 3″ (75 mm) and the radius of fillet is 0.354″ (9 mm).

2.2 Cold Expansion Process and Test Matrix

2.2.1 Cold Expansion Process

The standard split-sleeve cold expansion procedure (FTI Specification 8101D) developed by Fatigue Technologies Incorporated (FTI, 2002) was used for cold expansion of the open hole in the Geometry-1 specimens. The FTI cold expansion procedure involves mechanically pulling an oversized mandrel through the open hole to expand it to a desired expansion level (generally, 3% – 5%), as illustrated in Figure 4. The desired finished hole diameter and finish is normally obtained by reaming, which also removes any tool marks or potential crack initiation sites. During the split-sleeve cold expansion process, a protective stainless steel sleeve with an axial split is placed between the mandrel and the hole bore to provide for the expansion. In this study, the average applied expansion was about 3.4%, which is slightly less than a typical 4% reported in the literature. The degree of the cold expansion is defined by the relation:

$$CX\% = \frac{D_{cw} - D_0}{D_0} \times 100\% \tag{2}$$

Where D_0 and D_{cw} are the diameters of the hole before and after cold expansion, respectively (Ball & Lowry, 1998; FTI, 2002).

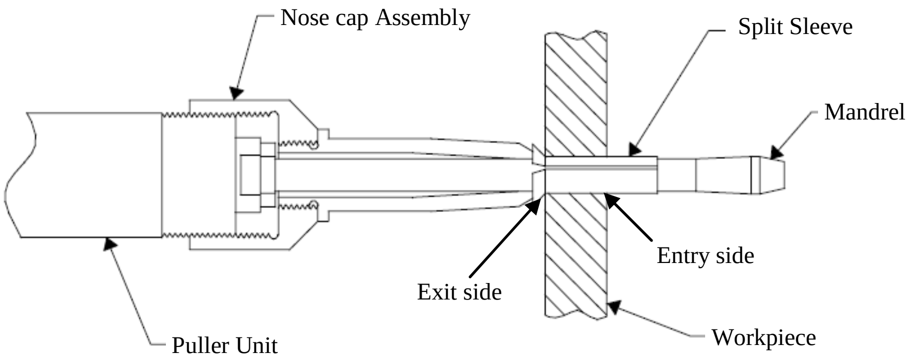


Figure 4 Split sleeve cold expansion (FTI, 2002).

2.2.2 Static Tensile and Fatigue Test Matrices

Static tensile tests were carried out on the cylindrical specimens without thermal exposure and on the cylindrical specimens exposed to 350°F (177°C) for 1, 3, 6 and 8 hours, in accordance with ASTM B557M.

Prior to fatigue testing, the cold expanded and non-cold expanded open hole specimens, and the specimens without an open hole were exposed to a temperature of 350°F (177°C)

for 1, 3, 6 and 8 hours. The fatigue test matrices are given in Table 3 and Table 4, for specimen geometries 1 and 2, respectively.

Table 3. Test matrix for Geometry-1 of 7050 Al alloy (KK) with open hole

Conditions	**Room Temp.**	**Thermal Exposure at 350°F (177°C)**			
		1 Hr	3 Hr	6 Hr	8 Hr
Non-cold expanded	✓	N/A	✓	N/A	✓
Cold expanded	✓	✓	✓	✓	✓

Table 4. Test matrix for Geometry-2 of 7050 Al alloy (LM) (without open hole)

Conditions	**Room Temp.**	**Thermal Exposure at 350°F (177°C)**			
		1 Hr	3 Hr	6 Hr	8 Hr
Plain (No open hole)	✓	✓	✓	✓	✓

2.3 Measurements of Electrical Conductivity and Hardness

2.3.1 Electrical Conductivity

To assess the effect of thermal exposure history, the electrical conductivity of the thermally exposed and the non-thermally exposed specimens were measured using a calibrated Sigma Test D-2.068 eddy current electrical conductivity test apparatus with a 13.4 mm shielded probe and at a frequency of 60 kHz, using the standard procedure (SAE 2003b). The measured electrical conductivity is expressed as a percentage of the International Annealed Copper Standard (%IACS). In the current test program, all conductivity tests were performed at room temperature in a controlled laboratory environment. The test instrument was calibrated using copper and manganin calibration standards, prior to commencement as well as during the conductivity measurements. Five conductivity measurements were taken on each specimen.

2.3.2 Hardness

To assess the influence of thermal exposure on hardness and consequently any signs material degradation, Rockwell hardness (B scale, HRB) measurements were performed using a calibrated Wilson Rockwell hardness tester on specimens representative of the various thermally exposed and room temperature conditions. For each condition, at least three indentations (measurements), on both the top and bottom surfaces of the specimen (i.e., a total of six indentations per specimen), were made in accordance with Australian Standard-AS 1815-1991 "Metallic Material-Rockwell Hardness Test" and the average hardness value computed.

2.4 Fatigue Testing

All the fatigue tests were conducted at room temperature (68°F (20°C)), using a digitally controlled 100 kN MTS machine with a closed loop servo-hydraulic load-frame, under load control mode. Constant amplitude loading was applied. The test frequency was 10 Hz and the stress ratio ($\sigma_{min}/\sigma_{max}$ = R) was 0.1. The gross stress concentration factor (K_{tg}) was 3.16 and the net section stress concentration factor (K_{tn}) was 2.48, for the final hole-diameter of 0.28 inch (7.03 mm) in the Geometry-1 specimens (Peterson, 1997). A minimum of 3 specimens were tested for each condition.

The specimens were loaded under constant amplitude with an applied net stress of 22.77 ksi (157 MPa). That is, the maximum applied stress at the edge of a hole in the Geomtery-1 specimens is about 56.56 ksi (390 MPa). The same external maximum applied stress (i.e., 56.56 ksi (390 MPa)) was applied to the Geometry-2 specimens.

2.5 Fractographic Examination

The fracture morphologies of the non-cold expanded and cold expanded open hole specimens were examined using a scanning electron microscope (SEM) and an optical microscope with a digital image capture system.

3. Experimental Results and Discussion

3.1 Electrical Conductivity and Hardness

Electrical conductivity and hardness are measurable physical properties for heat treatable aluminium alloys which characterise the condition of the alloy. Hardness and conductivity are used for quality assurance as accept/reject criterion after heat treatment of aluminium alloys during component manufacture. Hardness and conductivity may also be used to assess the extent of heat damage in high-strength, precipitation hardenable aluminium alloys (Hagemaier, 1982; Wu, et al, 1996; Calero & Turk, 2005). In the current investigation, electrical conductivity and hardness were used to assess the effects of thermal exposure at a temperature of 350^{o}F (177^{o}C) for exposure times of 1, 3, 6 and 8 hours. One of the consequences of high temperature exposure of heat-treatable aluminium alloys is coarsening and/or dissolution of strengthening precipitates, causing strength/hardness reduction, and a change in electrical conductivity, depending on the exposure time at a given temperature, for the particular aluminium alloy.

3.1.1 Electrical Conductivity

Figure 5 shows the electrical conductivity of cold expanded open hole AA7050 aluminium alloy specimens as a function of exposure time at 350^{o}F (177^{o}C). The (68°F (20°C)) conductivity of the pristine material is also included in the Figure (i.e., zero thermal exposure time). It will be noted that electrical conductivity increases as the exposure time increased. The electrical conductivity at room temperature (68°F (20°C)) was 40.75%IACS. The maximum electrical conductivity of 42.03%IACS was reached at an exposure time of 8 hours, but that conductivity value was still within the acceptable range of 40.0%IACS - 44.0%IACS for the AA7050 aluminium alloy heat treated to the T7451 temper (SAE 2003b), suggesting that no serious electrochemical imbalance had occurred after 8 hours exposure at 350^{o}F (177^{o}C). It should be noted that cold expansion does not contribute to any change in electrical conductivity. All the observed increase in electrical conductivity is purely a bulk microstructural/material characteristic influenced only by the thermal exposure.

3.1.2 Hardness

Rockwell hardness (B scale; HRB) test results as a function of exposure time at a given temperature are shown in Figure 6. As expected, the hardness decreased as the exposure time increased, indicating a gradual softening of the material. For example, after 1 hour exposure, the average hardness was about 81.3 HRB in the cold expanded condition, but the hardness was decreased to about 77.7 HRB for an 8 hour exposure. For comparison, the non-cold expanded hardness results are also included in this Figure. The trends in hardness with exposure times were similar for both conditions. The hardness decreased below the minimum value (HRB~82) prescribed in AMS 2658B (SAE, 2003b) when the specimen was exposed to high temperature for even the shortest exposure time of 1 hour.

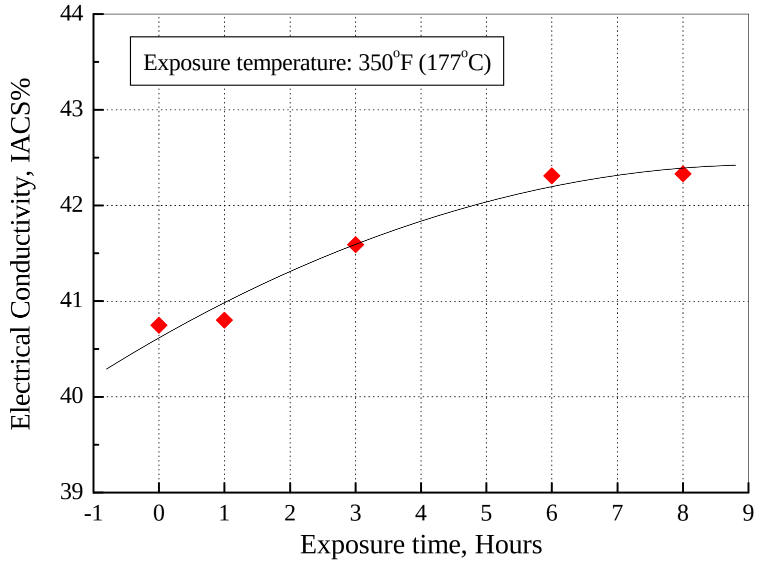


Figure 5. Electrical conductivity of cold expanded 7050 Al alloy exposed to 350°F (177°C) at different exposure times (hours)

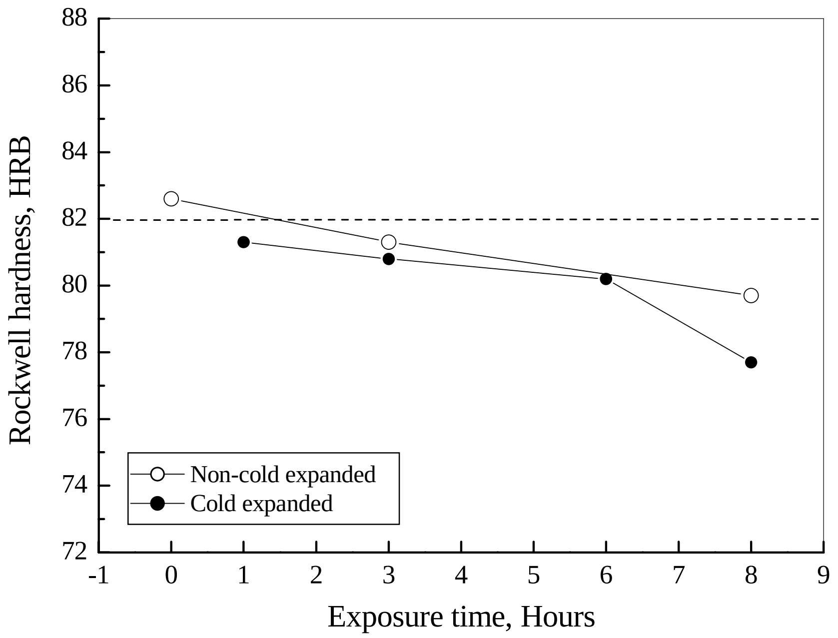


Figure 6. Rockwell hardness (HRB) of non-cold expanded and cold expanded 7050-T7451 aluminium specimens exposed to 350°F (177°C) at different exposure times (hours). The dashed line indicates the minium value prescribed in AMS 2658B (SAE, 2003b).

3.2 Static Strengths

Figure 7 shows the stress-strain curves from the tensile tests for the non-thermally exposed and thermally exposed AA7050-T7451 aluminium alloy specimens. After thermal exposure at 350°F (177°C) for 8 hours, the material is much softer and the strengths are lower than the test results achieved for the pristine material without thermal exposure. Figure 8 shows the effect of thermal exposure time on the yield and ultimate strengths. The yield strength fell below the minium allowable value (SAE, 2003a) after 1 hour exposure. With increasing exposure time, both the 0.2% yield strength and ultimate tensile strength decreased linearly. In other words, the loss of the static strength depends on the exposure time at a given temperature of exposure. For example, after 8 hours exposure the loss in 0.2% yield strength is about 19%[1], compared to the specimen without thermal exposure (see Table 5). But for 1 hour exposure, the loss in 0.2% yield strength was less than 6%.

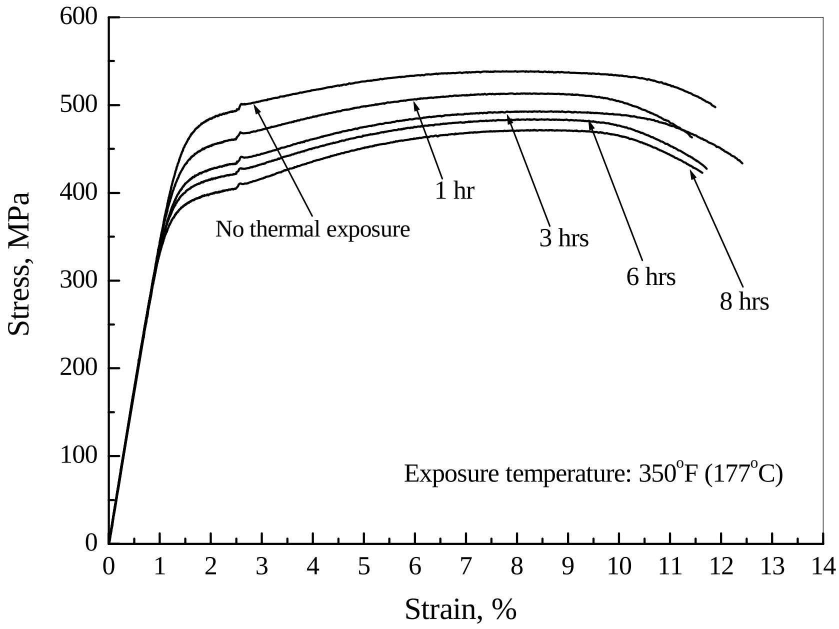


Figure 7. Stress-strain curves from tensile specimens at different exposure times for 350°F (177°C). The numbers in the figure are exposure time (hours)

Table 5. Loss in yield strength as a percentage of yield strength for AA7050 Al alloy at different thermal exposure times at 350°F (177°C)

Exposure Time (Hour)	0	1	3	6	8
Loss in Yield Strength (%)	0	5.7	12.3	15.2	18.9

Note: The yield strength without thermal exposure is the reference point (100%).

[1] The loss in yield strength is expressed as a percentage reduction relative to the baseline yield strength.

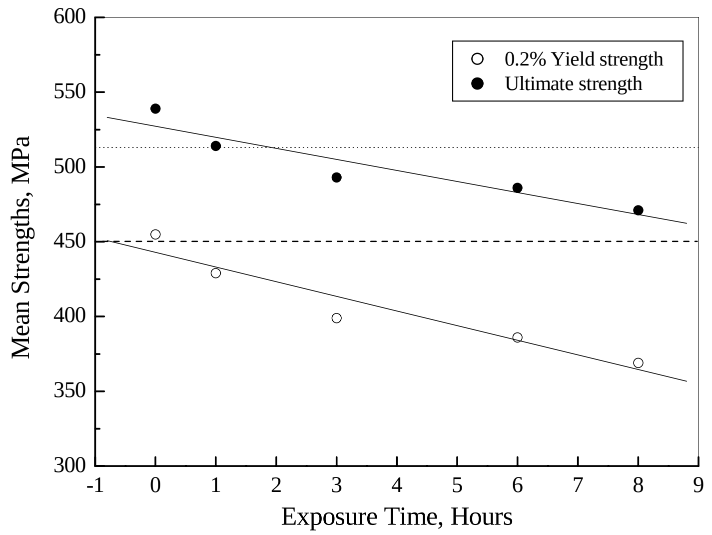


Figure 8. Static yield and ultimate strengths as a function of thermal exposure time at 350°F (177°C) for AA7050 aluminium alloy. The dashed and dot lines are the minimum values of yield and ultimate strengths of AA7050 aluminium alloy, respectively (SAE, 2003a).

3.3 Fatigue Life

Figure 9 shows the average fatigue lives (for constant amplitude loading; net-stress = 22.77 ksi (157 MPa)) of the cold expanded, open hole AA7050 specimens exposed at a temperature of 350°F (177°C) for various exposure times. Thermal exposure resulted in decreased fatigue life, possibly due to relaxation of the compressive residual stresses originally induced by the cold expansion process. For example, after the specimens were exposed to 350°F (177°C) for 1 hour, the average fatigue life was decreased from several million cycles for the unexposed specimen condition, to about 510,000 cycles after 1 hour exposure, and to around 300,000 cycles after 3 hours exposure. When the exposure time was longer than 3 hours, little further reduction in fatigue life was observed. The average fatigue life after 6 hours was around 260,000 cycles.

It was found that the effect of thermal exposure on the fatigue life of non-cold expanded specimens with the same specimen geometry was less severe than that of the cold expanded open hole specimens, as shown in Figure 10. A large fatigue life improvement was obtained for cold expanded open hole specimens compared to non-cold expanded specimens, even after thermal exposure. A similar result was also observed by Lacarac, et al. (2001) and the fatigue life improvement factor was between 1 and 10, depending on the degree of exposure. In this work, the fatigue life improvement for cold expansion was still retained at about 3~4 times that of non-cold expanded specimens (Figure 10) under the thermal exposure conditions investigated.

For the specimens without an open hole (geometry-2), the effect of the thermal exposure was slightly complicated because of a large degree of scatter in the test results, as shown in Figure 11. However, after exposure for 3 hours, the average fatigue lives were more or less

similar, at about 260,000 cycles. This is consistent with the observed results for the cold expanded open hole specimens (Figure 9).

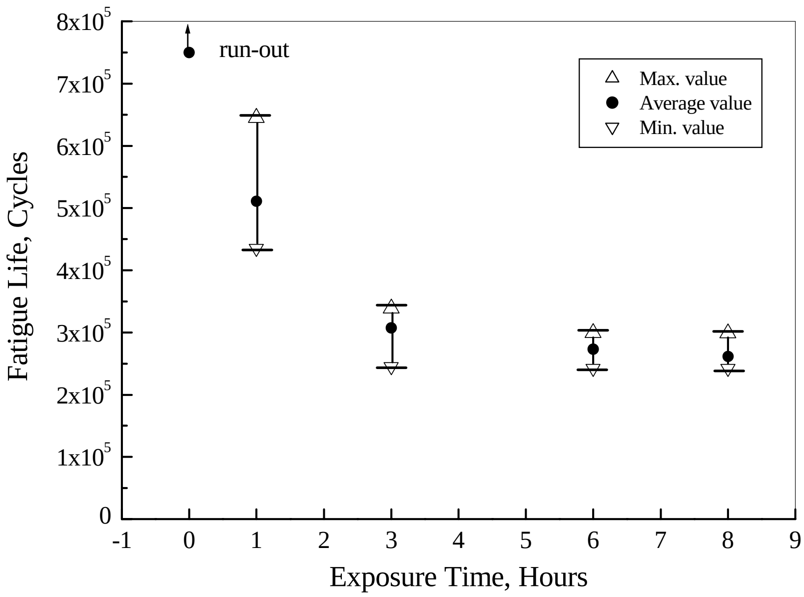


Figure 9. Fatigue lives of AA7050-T7451 aluminium alloy specimens with cold expanded open holes (Geometry-1) as a function of thermal exposure time at 350°F (177°C). Constant amplitude loading was applied with maximum net stress of 22.77 ksi (157 MPa) (equivalent to 56.56 ksi (390 MPa) maximum stress applied at the edge of the hole), at a frequency of 10 Hz and an R ratio of 0.1.

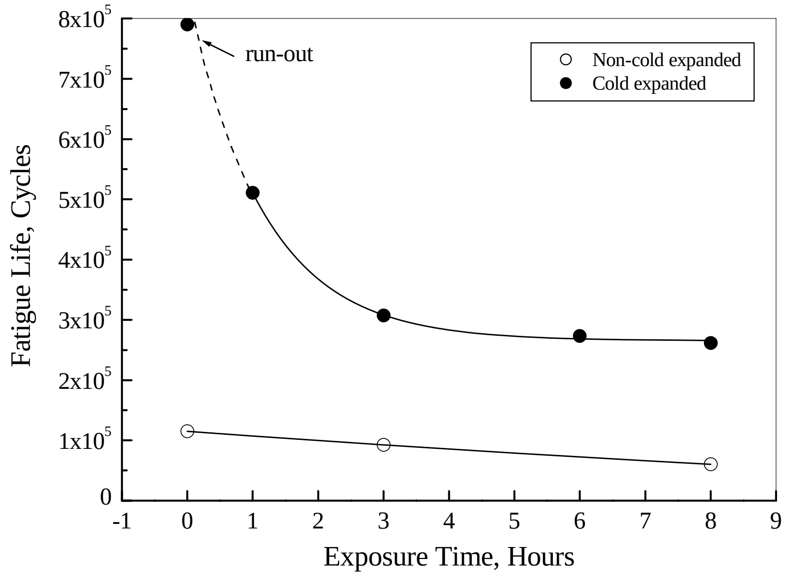


Figure 10. Comparison of the effect of thermal exposure on average fatigue life of cold expanded and non-cold expanded open hole in AA7050-T7451 aluminium alloy specimens. Constant amplitude loading was applied with the maximum net stress of 22.77 ksi (157 MPa) (equivalent to 56.56 ksi (390 MPa) maximum stress applied at the edge of the hole), at a frequency of 10 Hz and an R ratio of 0.1. The exposure temperature was 350°F (177°C).

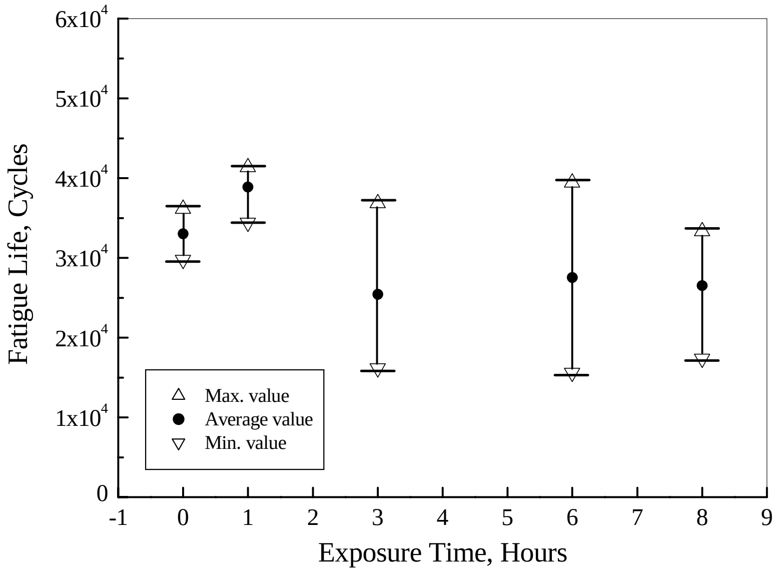
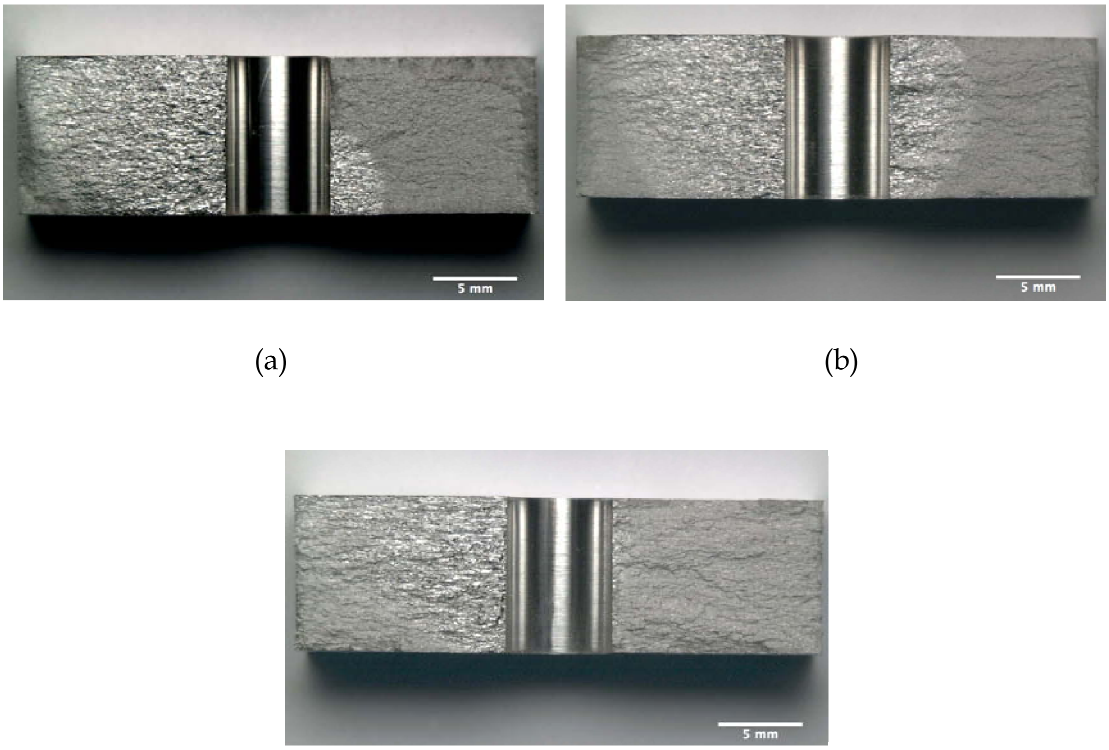


Figure 11. Fatigue lives of AA7050-T7451 aluminium alloy dog-bone specimens (Geometry-2) as a function of thermal exposure time at 350°F (177°C). Constant amplitude loading was applied with a maximum applied stress of 56.56 ksi (390 MPa), at a frequency of 10 Hz and an R ratio of 0.1.

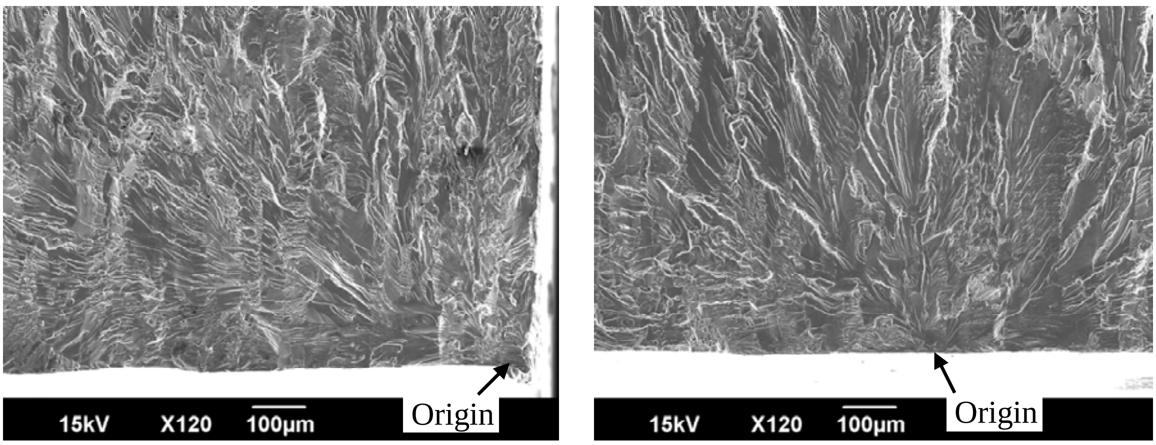
3.4 Fracture Morphology

The fracture surfaces of selected cold expanded and non-cold expanded open hole specimens were examined using optical and a scanning electron microscopes. The fracture surfaces of non-cold expanded specimens revealed a generally regular macroscopic crack front (i.e. across the width of the specimen), suggesting relatively uniform crack growth from initiation (Figure 12). It was also observed that cracking initiated randomly either at the corner of the hole, or in the bore of the hole, as shown in Figure 13. In contrast, the crack front shape in the cold expanded open hole specimens (see Figure 14) was macroscopically irregular across the width of the specimens suggesting non-uniform crack growth, probably arising from non-uniform, through thickness residual stresses at the hole.



(c)

Figure 12. Crack front shapes of the non-cold expanded specimens for different exposure times at 350°F (177°C) showing that the cracks initiated randomly either at the hole corner or in the bore of the hole: (a) 3 hours and (b) 8 hours, For comparison, the room temperature fracture surface is also included (c).



(a) (b)

Figure 13. Examples of crack origins in non-cold expanded specimens: (a) at the hole corner, and (b) in the bore of the hole.

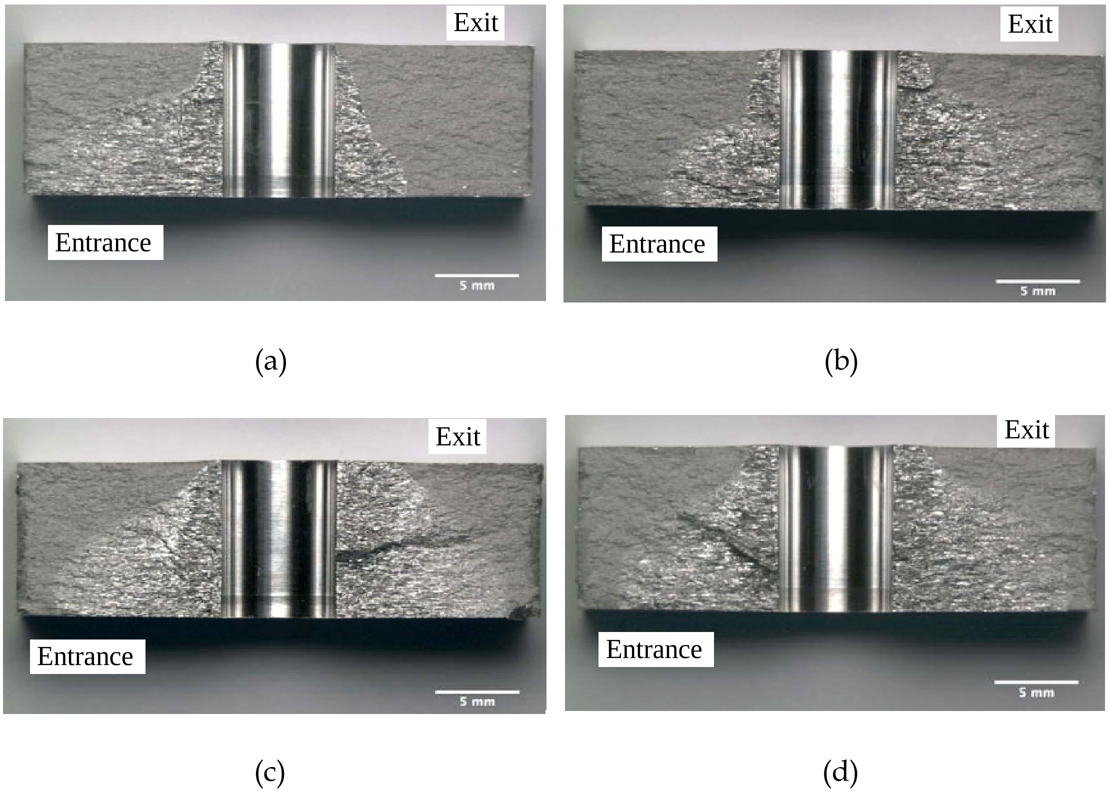


Figure 14. Crack front shapes of the cold expanded open hole specimens for different exposure times at 350°F (177°C): (a) 1 hour; (b) 3 hours; (c) 6 hours and (d) 8 hours. Cracking in the cold expanded open hole specimens generally initiated at or near the hole corner on the mandrel entrance side of the specimen.

For the cold expanded open hole specimen, the residual stresses at both the mandrel entrance and exit sides have been shown to be different (Stefanescu, et al, 2004), as shown in Figure 15. The differences in residual stresses is reflected in the differences in crack growth at the mandrel entrance and exit sides of the cold expanded open hole specimens (Figure 14). In the current investigation, the crack growth on the entrance side was faster than on the exit side. Other researchers have also shown that crack growth on the entrance side was faster and became dominant (Pell, et al, 1989; Holdway, et al, 1994). This phenomenon can be explained by the fact that the compressive residual stress on the mandrel exit side is higher than on the entrance side (Stefanescu, et al, 2004; Priest, et al, 1995) (Figure 15). In contrast, in the absence of a residual stress contribution, the non-cold expanded specimens showed generally similar and uniform crack growth behaviour across the width of the specimens at the bolt hole (Figure 12).

Although multiple crack initiation in the through-thickness direction for each of the cold expanded open hole specimens was observed, as shown in Figure 16, the primary crack initiated exclusively at or near the hole corner on the mandrel entrance side. Crack growth

behaviour would also be affected by the relaxation of residual stresses due to thermal exposure. However, almost no change in the crack shape was observed in the cold expanded open hole specimens for different exposure times (Figure 14).

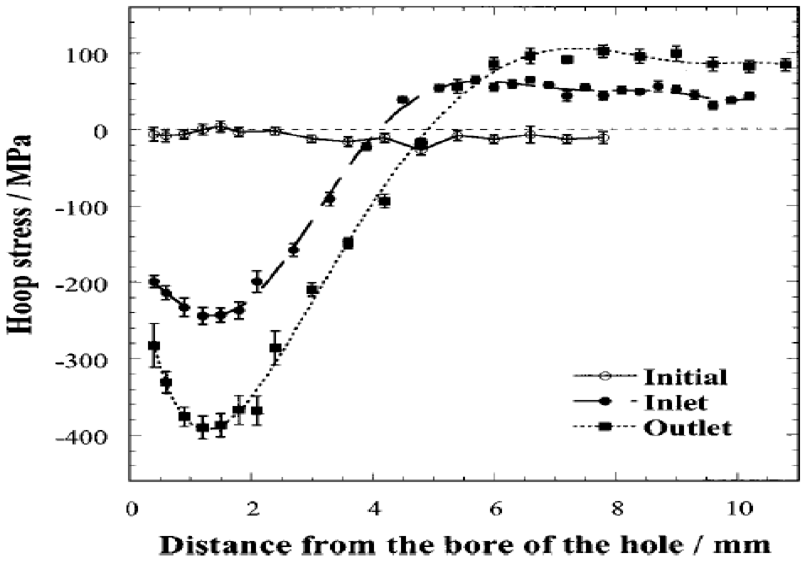
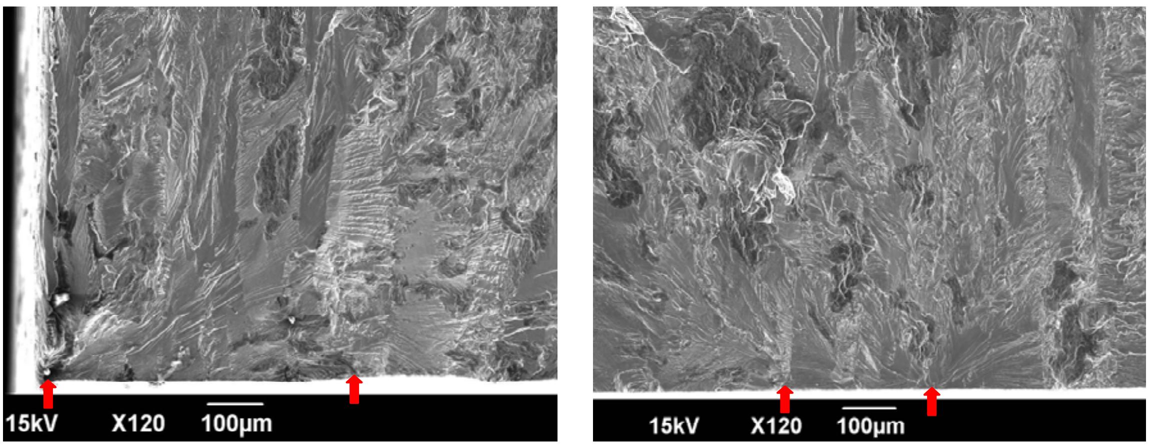


Figure 15. Hoop residual stress distribution measured using the X-ray diffraction technique along the transverse direction of the specimen before and after 4% cold expansion (Stefanescu, et al., 2004).



(a) (b)

Figure 16. Multiple crack origins found in the same cold-expanded specimen: (a) at the hole corner and (b) at the bore of the cold expanded hole. The arrows indicate the crack origins.

4. Conclusion

The effect of thermal exposure at 350°F (177°C), for different exposure times, upon the fatigue behaviour of non-cold and cold expanded open hole specimens as well as specimens without an open hole, manufactured using AA7050 aluminium alloy has been investigated by DSTO. The static tensile properties of cylindrical specimens at the same exposed condition were also documented. From the experimental results obtained in this investigation, the following conclusions can be drawn:

(1) For a given exposure temperature of 350°F (177°C), the fatigue life of the specimens decreased with increasing exposure time, probably due to relaxation of the beneficial compressive residual stresses. When the exposure time exceeds 3 hours, the fatigue life remained relatively unchanged;

(2) The fatigue life of the thermally exposed cold expanded specimens was found to be 3~4 times that of the non-cold expanded open hole specimens despite the high temperature exposure of 350°F (177°C);

(3) At the exposure temperature of 350°F (177°C), the yield strength of the specimens decreased linearly with increasing exposure time and fell below the minium allowable value (SAE, 2003a) after 1 hour exposure. After 8 hour exposure, the yield strength was about 19% lower than that of the specimens without thermal exposure (Table 5);

(4) The electrical conductivity (%IACS) of the specimens increased with increases in exposure time. However, the conductivity remained within the specification limits set by AMS 2658B for the alloy and temper;

(5) The hardness (Rockwell scale, HRB) of the specimens decreased as the exposure time increased. The hardness decreased below the minimum value (HRB~82) prescribed in AMS 2658B when the specimen was exposed to high temperatures regardless of exposure time. Significant change in hardness only occurred after exposure for 8 hours;

(6) The fractographic observation showed that for the cold expanded open hole specimens, in general, crack growth on the mandrel entrance side was dominant, probably due to the compressive residual stress on the mandrel exit side being greater than on the entrance side.

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Cold Expansion, High Temperature Exposure, Fatigue Life, Hardness, Conductivity, Aluminium Alloy 7050-T7451

19. ABSTRACT

Cold expansion of fastener holes has been widely used in the manufacture, maintenance and repair of airframe components to provide beneficial compressive residual stresses around fastener holes and to extend their fatigue life. However, some components may experience exposure to high temperatures due to operational, maintenance or accidental factors. The high temperature exposure could lead to relaxation of compressive residual stresses and potentially affect the component's properties such as fatigue life and static strength properties. This report summaries the investigation on the effect of exposure time at a temperature on the mechanical properties of cold expanded open holes in 7050-T7451 aluminium alloy. The experimental results show that for a given exposure temperature of 350°F (177°C), the fatigue life of the specimens decreased with increasing exposure time. When the exposure time exceeds 3 hours, the fatigue life remained relatively unchanged. The yield strength at the same exposure temperature fell below the minimum allowable value after 1 hour exposure.